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EXAMINATION OF RESIDUAL STRESSES ON DIAMOND BURNISHED CYLINDRICAL SURFACES

ABSTRACT

Cold plastic finish manufacturing methods such as surface rolling, burnishing and surface hardening with shot peening play important role in the lifetime increasing manufacturing as compressive residual stress remains in near surface layers of the workpiece. This paper deals with examination of changing of residual stress caused by burnishing using diamond tipped tools. The diamond burnishing executed on outer cylindrical surfaces is a finishing manufacturing operation which results high accuracy and fine surface texture. The aim of the examinations was to determine how the burnishing speed, feed rate and burnishing force has affect on the residual stresses in case of diamond burnishing of low alloyed aluminium shafts. The Taguchi type Factorial experiment design was used for planning of experiments. The measurement of residual stresses was performed by an X-ray diffraction method. The evaluation of measured results was done by a specially specified ratio to determine the parameter set which results the best residual stress values in between the given range of technological parameters.

1. INTRODUCTION

Nowadays, the researches regarding shape correctness [1] and surface roughness of the manufactured surfaces [2 - 4] are accelerated. More and more researches deal with residual stresses [5] and the examination of changing of texture on the surface of the workpiece [6]. This is in connection with the tasks determined in Industry 4.0 as well in which the development of production engineering and manufacturing processes is an important task. These tasks can be done in environmentally conscious way too [8 - 9]. These are in tight connection with the lifetime and reliability [10] of the produced parts. The accuracy of differently manufactured parts were analysed, examined, and compared [11] because parts can be produced with higher and higher accuracy by the newly developed cutting tools [12 - 14]. Life time of products can be increased in profoundly great extent by assembling these parts into the engineering products.

In industrial practice, the quality requirements involve the knowledge of the value and distribution of residual stresses in the near surface layer particularly parts of motor vehicle exposed to fatigue. There are several possibilities for direct creation of compressive stress for preventing of the development and spread of fatigue cracking such as cementing, blasting, calendaring and roll burnishing [15]. Burnishing of surfaces belongs to here as well, which can be more effective, more efficient than conventional fine surface machining procedures (e.g. grinding, lapping, polishing). Burnishing can make manufacturing process more cost effective.

The Taguchi type factorial experimental design was used in this research [16 - 17] which is valid in between the minimum and maximum values of the input parameters. The classification and short description of design of experiment methods was prepared by Drégelyi-Kiss et. al. [18].

In the present experiments input parameters were: burnishing speed (vb), feed (f), and burnishing force (Fb) while the output parameters are: tangential (σt) and axial (σa) residual stress.

2. BURNISHING OF OUTER CYLINDRICAL SURFACES

During burnishing, because of the kinematic interaction of work piece and burnishing tool, the near surface layer of the work piece is deformed [19]. Kinematic relations are demonstrated in Fig. 1 [20].

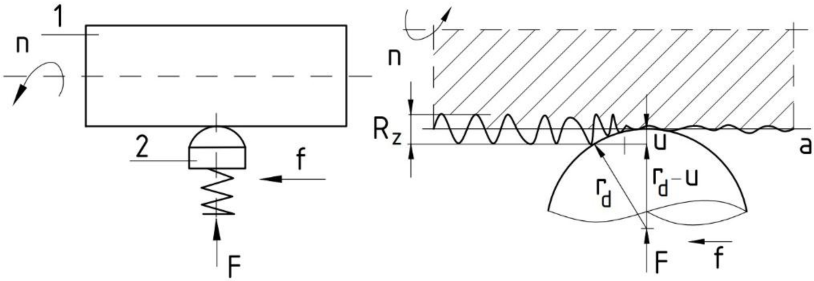


Figure 1 – Kinematics of burnishing [20]

There are several advantages of this procedure applying sliding relative movement: - surface roughness can be reduced effectively, - the micro hardness of near surface layer can be increased by reordering of dislocations, - corrosion resistant ability can be improved, - shape correctness of the cylindrical surfaces can be improved, - does not require huge amount of coolant and lubricant application, so means low environment load [21].

In case of outer cylindrical surfaces diamond burnishing is applied as a final finishing procedure resulting high accuracy, low surface roughness. The diamond burnishing can be realized on conventional lathes and CNC lathes as well. The applied tool tip can be hardened steel, carbide, ceramics, or natural or artificial diamond.

The reduction of surface roughness and the other advantages mentioned above occur because of static contact being in between of burnishing tool and surface of work piece, typically in the depth of 0,01÷0,2 mm [22 - 25]. During the manufacturing process, the tensile residual stress being in the surface zone after machining is converted into compressive residual stress which is the cause that fatigue behaviour is improving of the part under dynamic load.

3. EXPERIMENTAL CONDITIONS

3.1. Features of the workpiece to be burnished

The material and the hardness of the workpiece to be burnished can be differed for a very wide range. For the experiments, we have chosen lightly alloyed aluminium material because it's employment is supported for choice by industries [26 - 29], due to its low density and good mechanical properties.

The examination of the chemical composition of the lightly alloyed aluminium was executed on a scanning electron microscope type Apollo X. Measuring was done on 3 points and the averaged results are shown in Table 1.

Table 1 – Chemical composition of the aluminium alloy

Elements	Al	Si	Fe	Cu	Bi	Pb
Averaged wt% (weight percent)	92.11	0.19	0.84	5.65	0.46	0.74

3.2. Burnishing parameters

During the experiments, a CNC lathe with flatbed by firm OPTIMUM type OPTIturn S600 was used which is located in the workshop of Institute of Manufacturing Science at University of Miskolc. The tool tip was PCD (polycrystalline diamond) with 3.5 mm radius and the kinematic viscosity of the applied oil was 70 mm2/s. Fig. 2 shows the process in progress.

The matrix of the Taguchi type Full Factorial Experimental Design can be seen on Table 2, which contains the burnishing parameters in natural dimensions and their transformed values.

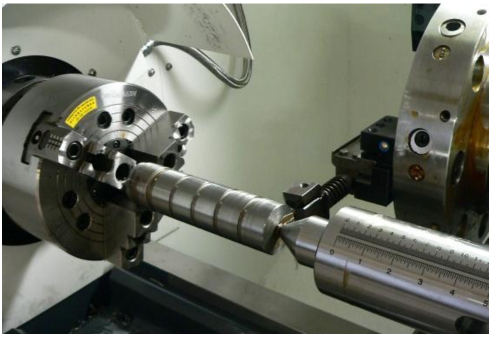


Figure 2 – Burnishing process on OPTIMUM OPTIturn CNC machine

Table 2 – Applied burnishing parameters

Sign of specimen	Parameters of burnishing			Transformed parameters		
	v_b [m/min]	f [mm/rev]	F_b [N]	x_1	x_2	x_3
1	15	0.001	10	-1	-1	-1
2	30	0.001	10	+1	-1	-1
3	15	0.005	10	-1	+1	-1
4	30	0.005	10	+1	+1	-1
5	15	0.001	20	-1	-1	+1
6	30	0.001	20	+1	-1	+1
7	15	0.005	20	-1	+1	+1
8	30	0.005	20	+1	+1	+1

3.3. Measuring of the residual stress

Residual stress is a process-induced stress, frozen in a molded part, that exists in a body in the absence of external loading or thermal gradients. In a structural material or component, residual stresses exist in the object without the application of services or other external loads. They affect a part similarly to externally applied stresses.

Important residual stress measurements are made by the following methods: hole-drilling method, magnetic field, ultrasonic testing and X-ray diffraction method [30].

In materials because of the macroscopic residual stress the atomic cores in the lattice points are put of their balance [31]. In the point of view of crystallography, it means that the parameters of the lattice are changing. Distance between lattice planes are changed because of the residual stress, these distances can be measured, so the values of the stress can be calculated from them.

Incidentally residual stress can be hardly established in lower rigid materials. It causes smaller changing in material properties as it can be more relaxed [22].

During measuring process, the wave-length of the X-ray is known and the dislocation of the Bragg-angle is measured that is caused by the changing of lattice planar distances. The formula (1) was applied what is called Bragg-equation [32]:

$$n\lambda = 2d_{hkl}\sin\Theta, \tag{1}$$

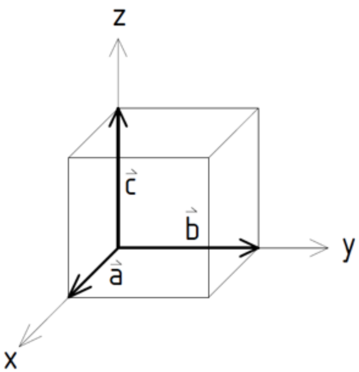
where: n: integer determined by order given

λ: wave-length of X-ray

d_{hkl}: spacing between the planes in the atomic lattice

Θ: angle between the incident ray and the scattering planes

Fig. 3 [33] illustrates crystal co-ordinate system with the applied marks and calculating methods.



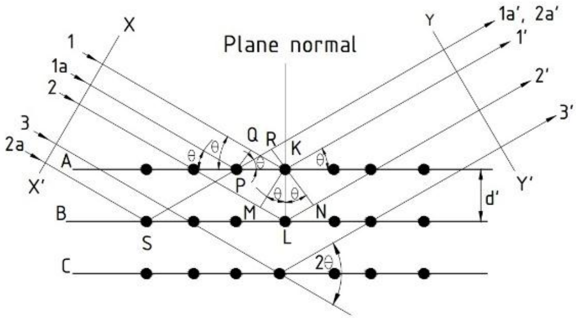
$$\frac{x}{a}+\frac{y}{b}+\frac{z}{c}=1$$

$$h=\frac{1}{a}\quad k=\frac{1}{b}\quad l=\frac{1}{c}$$

Figure 3 – Demonstration of crystal systems [33]

Fig. 4 illustrates the basic principles of the described method with its adaptation into practice which was executed on an X-ray diffraction measuring machine type Stresstech Xstress 3000 G3R. One of the main advantage of using this measuring machine is that it can realize non-destruction test.

a)



b)

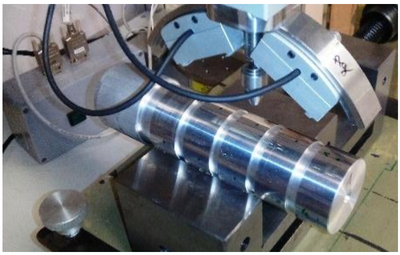
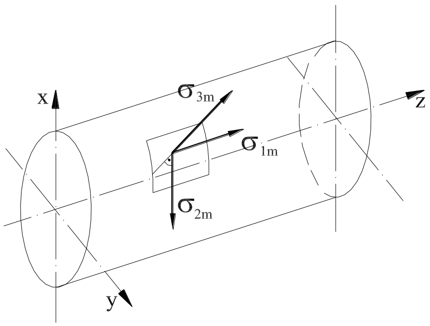


Figure 4 – Diffraction of X-ray method
a) theoretic background by a crystal lattice [32], b) and realization

The diffraction of X-rays, of course, was not only between 2 nearby atomic planar, they are reflecting forward. The X-rays landed from this further planer have to meet in the same phase and the criterion of it is that the difference of device between reflected waves being equal to integral multiples of wave-length, so in formula (1) n = 1, 2, 3, ... must be substituted [32].

Measuring was done on 4 points at 45° in tangential and axial direction too because it was supposed that the direction of the processing has influence on the changing of the stress condition. Fig. 5 shows the main stress directions [34].



$\sigma_{1m} = \sigma_a$ - axial residual stress,
$\sigma_{2m} = \sigma_t$ - tangential residual stress,
$\sigma_{3m} = \sigma_r$ - radial residual stress,
+ means tensile residual stress,
- means compressive residual stress.

Figure 5 – The main stress direction of cylindrical workpiece [34]

4. RESULTS AND EVALUATIONS

For evaluation of measured data an improvement ratio was introduced, which is shown in formula (2):

$$\rho_\sigma = \frac{|\sigma_b - \sigma_t|}{|\sigma_b|} \cdot 100, \% \qquad (2)$$

where: ρ_σ Improvement ratio of residual stresses (σ). This is a dimensionless ratio, which textures the changing of residual stress occurring because of manufacturing,

σ_t Residual stress remains after turning,

σ_b Residual stress remains after burnishing.

The higher the value of ρ_σ, the greater the improvement due to burnishing. Measured data and the improvement ratios of residual stresses, calculated by formula (1), in tangential and axial directions are summarized in Table 3.

Table 3 – Measured residual stress values and the calculated improvement ratios

Sign of specimen	σ_t [MPa]		$\rho_{\sigma t}$ [%]	σ_a [MPa]		$\rho_{\sigma a}$ [%]
	after turning	after burnishing		after turning	after burnishing	
1	23.470	- 97.230	124.14	- 6.075	- 163.300	96.27
2	23.470	- 148.350	115.82	- 6.075	- 191.625	93.83
3	23.470	- 209.325	111.21	- 6.075	- 220.500	97.24
4	49.250	- 200.352	124.58	10.475	- 294.975	103.55
5	23.470	- 89.600	126.19	- 6.075	- 105.875	94.26
6	49.250	- 71.800	168.59	10.475	- 82.575	112.69
7	23.470	- 131.475	117.85	- 6.075	- 207.950	97.08
8	49.250	- 150.075	132.82	10.475	- 241.125	104.34

Application of Factorial Experiment Design method empirical formulas (3) and (4) were created from the calculated values. Calculations and axonometric figures (Fig. 6-7) were prepared using „MathCAD 16.0" software.

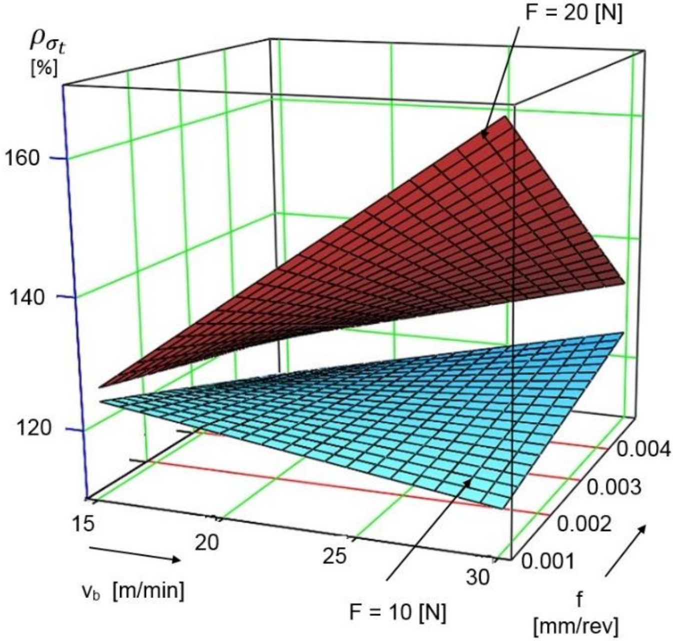


Figure 6 – Changing of improvement ratio of the residual stresses measured in tangential direction

$$\rho_{\sigma_t} = 203.2125 - 5.116 \cdot v_b - 2.208 \cdot 10^4 \cdot f - 6.21 \cdot F_b + 1.18 \cdot 10^3 \cdot v_b \cdot f + \\ +0.42 \cdot v_b \cdot F_b + 0.43 \cdot f \cdot F_b - 81{,}867 \cdot v_b \cdot f \cdot F_b \quad (3)$$

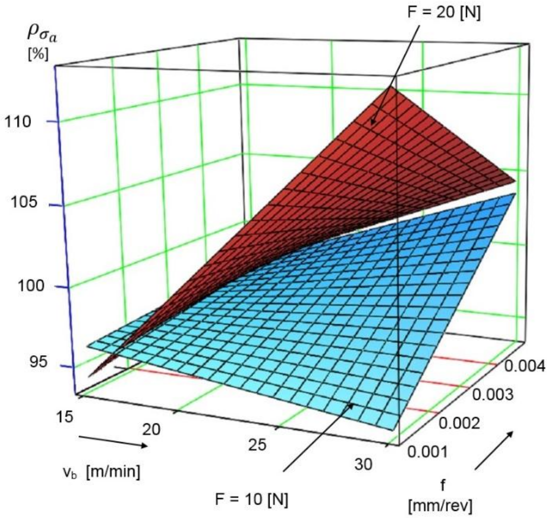


Figure 7 – Changing of improvement ratio of the residual stresses measured in axial direction

$$\rho_{\sigma_a} = 128.8275 - 2.027 \cdot v_b - 7.357 \cdot 10^3 \cdot f - 2.825 \cdot F_b + 476.833 \cdot v_b \cdot f + \\ + 0.172 \cdot v_b \cdot F_b + 542.75 \cdot f \cdot F_b - 33.15 \cdot v_b \cdot f \cdot F_b \quad (4)$$

5. SUMMARY

Following statements can be done on the base of executed and evaluated experiments:

In tangential direction, perpendicular to the direction of manufacturing, the value of the improvement ratio of residual stresses was the highest, $\rho_{\sigma t}$ = 168,59 %, when the burnishing parameters were: v_{b2} = 30 m/min; f_1 = 0.001 mm/rev; and F_{b2} = 20 N. Using these burnishing parameters, in axial direction the maximum value of the improvement ratio of residual stresses is $\rho_{\sigma a}$ = 112,69%.

Examining the evaluated results can be stated that the effect of burnishing speed is the most dominant when the burnishing force is higher (F_{b2} = 20 N) and the feed rate is smaller (f_1 = 0.001 mm/rev). The burnishing speed and burnishing force show strong interaction. It requires further investigation for what extent can these burnishing parameters increased further.

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